

An Identity Based Key Management Scheme in Wireless Sensor Networks

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Abstract

Pairwise key establishment is one of the fundamental security services in sensor networks which enables sensor nodes in a sensor network to communicate securely with each other using cryptographic techniques. It is not feasible to apply traditional public key management techniques in resource-constrained sensor nodes, and also because the sensor nodes are vulnerable to physical capture. In this paper, we introduce a new scheme called the identity based key pre-distribution using a pseudo random function (IBPRF), which has better trade-off between communication overhead, network connectivity and resilience against node capture compared to the other key pre-distribution schemes. Our scheme can be easily adapted in mobile sensor networks. This scheme supports the addition of new sensor nodes after the initial deployment and also works for any deployment topology. In addition, we propose an improved version of our scheme to support large sensor networks.

1 Introduction

In a sensor network, many tiny computing nodes called sensors, are scattered in an area for the purpose of sensing some data and transmitting the data to nearby *base stations* for further processing. The transmission between the sensors is done by short range radio communications. The base station is assumed to be computationally well-equipped whereas the sensor nodes are resource-starved. Such networks are used in many applications including tracking of objects in an enemy's area for military purposes, distributed seismic measurements, pollution tracking, monitoring fire and nuclear power plants, tracking patients, engineering and

medical explorations like wildlife monitoring, etc. Mostly for military purposes, data collected by sensor nodes need be encrypted before transmitting to neighboring nodes and base stations.

The following issues make secure communication between sensor networks different from usual (traditional) networks:

- *Limited resources in sensor nodes:* Each sensor node contains a primitive processor featuring very low computing speed and only small amount of programmable memory. An example is the popular Atmel ATmega 128L processor.
- *Limited life-time of sensor nodes:* Each sensor node is battery-powered and is expected to operate for only few days. Therefore, once the deployed sensor nodes expire, it is necessary to add some fresh nodes for continuing the data collection operation. This is referred to as the *dynamic management of security objects (like keys)*.
- *Limited communication abilities of sensor nodes:* Sensor nodes have the ability to communicate each other and the base stations by the short range wireless radio transmission at low bandwidth and over small communication ranges (typical example is 30 meters (100 feet)).
- *Lack of knowledge about deployment configuration:* Most of cases, the post deployment network configuration is not known a priori. As a result, it is unreasonable to use security algorithms that have strong dependence on locations of sensor nodes in a sensor network.

- *Mobility of sensor nodes:* Sensor nodes may be mobile or static. If sensor nodes are mobile then they can change the network configuration at any time.
- *Issue of node capture:* A part of the network may be captured by the adversary/enemy. The resilience measurement against node capture is computed by comparing the number of nodes captured, with the fraction of total network communications that are exposed to the adversary *not including* the communications in which the compromised nodes are directly involved.

Thus, it is not feasible to use public-key cryptosystems in resource constrained sensor networks. Hence, only the symmetric cipher such as DES/IDEA/RC5 [12, 11] is the viable option for encryption/decryption of secret data. But setting up symmetric keys among communication nodes is a challenging task in a sensor network. A survey on sensor networks can be found in [2, 1].

The topology of sensor networks changes due to the following three phases:

- *Pre-deployment and deployment phase:* Sensor nodes can be deployed from the truck or the plane in the sensor field.
- *Post-deployment phase:* Topology can change after deployment because of irregularities in the sensor field like obstacles or due to jamming, noise, available energy of the nodes, malfunctioning, etc., or due to the mobile sensor nodes in the network.
- *Redeployment of additional nodes phase:* Additional sensor nodes can be redeployed at any time to replace the faulty or compromised sensor nodes.

A protocol that establishes cryptographically secure communication links among the sensor nodes is called the *bootstrapping protocol*. Several methods [6, 3, 8, 5] are already proposed in order to solve the bootstrapping problem. All these techniques are based on random deployment models, that is, they do not use the pre-deployment knowledge of the deployed sensor nodes. Eschenauer and Gligor [6] proposed the basic random key predistribution called the EG scheme, in which each sensor is assigned a set of keys randomly selected from a big key pool of the keys of the sensor nodes. Chan et al. [3] proposed the q -composite key predistribution and the random pairwise keys schemes. For both the EG and the q -composite schemes, if a small number of sensors are compromised, it may reveal to compromise a large fraction of pairwise keys shared between non-compromised sensors. However, the random pairwise keys predistribution is perfectly secure against node captures, but there is a problem in supporting the large network. Liu and Ning's polynomial-pool based

key predistribution scheme [8] and the matrix-based key predistribution proposed by Du et al. [4] improve security considerably. Liu and Ning [10] proposed the extended version of the closest pairwise keys scheme [9] for static sensor networks. Their scheme is based on the pre-deployment locations of the deployed sensor nodes and a pseudo random function (PRF) proposed by Goldreich et al. [7]. There is no communication overhead for establishing direct pairwise keys between neighbor nodes and the scheme is perfectly secure against node capture.

The rest of the paper is organized as follows. Section 2 describes our proposed scheme called the identity based key predistribution using a pseudo random function (IBPRF). In Section 3, we provide a theoretical analysis for this scheme. In Section 4, we discuss the security issues with respect to our scheme. In Section 5, we provide an improved version of our scheme for distributed sensor networks. In Section 6, we compare our scheme with the previous schemes [6, 3, 8] with respect to communication overhead, network connectivity, and resilience against node captures. Finally, Section 7 concludes the paper.

2 Identity Based Key Pre-Distribution using a Pseudo Random Function (IBPRF)

The bootstrapping protocol for the random key predistribution schemes [6, 3, 8] incurs much more communication overhead for establishing direct pairwise keys between sensor nodes in a sensor network. Our goal is to design a protocol which basically reduces the communication overhead for establishing direct pairwise keys between sensors during direct key establishment phase of the bootstrapping. We propose a new scheme called the *identity based key predistribution using a pseudo random function* (IBPRF), which serves our above desired purpose.

IBPRF has the following interesting properties:

- There is no communication overhead during direct key establishment phase for establishing direct pairwise keys between sensors.
- There is no communication overhead during the addition of new sensor nodes.
- When the sensor nodes are mobile, our scheme easily establish direct pairwise keys between the mobile sensor nodes and their physical neighbors with which they do not share keys currently with some desired probability.

- It works for any deployment topology.

IBPRF is based on the following two ingredients:

- A pseudo random function (PRF) proposed by Goldreich et al. in 1986 [7].
- A master key (MK) shared between each sensor node and the key setup server.

The different phases for this scheme are as follows.

2.1 Key Pre-Distribution

Let N be a pool of the ids of n sensor nodes in a sensor network. Assume that each sensor node u is capable of holding a total of $m + 1$ cryptographic keys in its key ring K_u . The key predistribution has the following steps:

- *Step-1:* For each sensor node u , the key setup server randomly generates a master-key MK_u .
- *Step-2:* For each sensor node u , the key setup server selects a set S of m randomly generated ids of sensor nodes from the pool N which are considered as the probable physical neighbors' ids. Let $S = \{v_1, v_2, \dots, v_m\}$. For each node id $v_i \in S$ ($i = 1, 2, \dots, m$), the key setup server generates a symmetric key $SK_{u,v_i} = PRF_{MK_u}(u)$ as the pairwise key shared between the nodes u and v_i , where MK_{v_i} is the master key for v_i and u is the id of the node u .

For each $v_i \in S$, the key-plus-id combination (SK_{u,v_i}, v_i) is stored in u 's key ring K_u . We note that each node v_i can easily compute the same key SK_{u,v_i} with its master key and the id of node u . The sensor node v is called a master sensor node of u if the shared key between them is calculated by $SK_{u,v} = PRF_{MK_v}(u)$. In other words, node u is called a slave sensor node of v if v is a master sensor node of u .

2.2 Direct Key Establishment

After deployment of sensor nodes in a deployment area (i.e., target field), sensor nodes will establish direct pairwise keys between them. Direct key establishment phase has the following steps:

- *Step-1:* Each sensor node first locates its all physical neighbors. Nodes u and v are called *physical neighbors* if they are within the communication range of one another. They are called *key neighbors* if they share a pairwise key. They are said to be *direct neighbors* if they are both physical as well as key neighbors. Now, after identifying the physical neighbors

by a sensor node u , it can easily verify which ids of the physical neighbors exist in its key ring K_u . If u finds that it has the predistributed pairwise key $SK_{u,v} = PRF_{MK_v}(u)$ with node v then it informs sensor v that it has such a key. This notification is done by sending a short message containing the id of node u that u has such a key. We note that this message never contains the exact value of the key $SK_{u,v}$.

- *Step-2:* Upon receiving such a message by node v , it can easily calculate the shared pairwise key $SK_{u,v} = PRF_{MK_v}(u)$ by using its own master key and the id of node u .

Thus, nodes u and v can establish a direct pairwise key shared between them very easily and use this key for their future communication.

2.3 Path Key Establishment

This is an optional stage, if requires, adds the connectivity of the network. After direct key establishment, if the connectivity is still poor, nodes u and v which are physical neighbors not sharing a pairwise key, can establish a direct key between them as follows.

- *Step-1:* u first finds a path $\langle u = u_0, u_1, u_2, \dots, u_{h-1}, u_h = v \rangle$ such that each (u_i, u_{i+1}) ($i = 0, 1, 2, \dots, h - 1$) is a secure link.
- *Step-2:* u generates a random number k' as the shared pairwise key between u and v and encrypts it using the shared key SK_{u,u_1} and sends to node u_1 .
- *Step-3:* u_1 retrieves k' by decrypting the encrypted key using SK_{u,u_1} and encrypts it using the shared key SK_{u_1,u_2} between u_1 and u_2 and sends to u_2 .
- *Step-4:* This process is continued until the key k' reaches to the desired destination node v .

As a result, nodes u and v use k' as the direct pairwise key shared between them for future communication. Since this process involves more communication overhead to establish a pairwise key between nodes, in practice $h = 2$ or 3 is recommended.

2.4 Mobility of Sensor Nodes

Suppose that a sensor node u moves from one location to another. Due to location updation of u , the connectivity of u with the new neighbors may also change. In the new location, assume that u finds the ids of its some new physical neighbors with which it does not currently share any keys. If v be one such physical neighbor, u informs to v that it has a pairwise key with v . This notification takes

place by sending a request message to v containing the id of sensor node u excluding the exact value of the key. Upon receiving this message, v can immediately compute the pairwise key shared between them by executing one efficient PRF operation and by using the master key MK_v for v and the id of sensor node u . Thus, u and v use this key for their future communication.

After performing this stage, if sensor node u finds still poor connectivity, it may opt for at most 1-hop path key establishment because path key establishment involves more communication overhead. Of course we assume that mobility of sensor nodes are infrequent.

2.5 Addition of Sensor Nodes

In order to add a new sensor node u , the key setup server selects a set S of m randomly generated ids of sensor nodes from the pool N . The key setup server randomly generates a master key MK_u for node u . For each sensor node id $v \in S$, the key setup server takes the master key MK_v and compute the secret key $SK_{u,v} = PRF_{MK_v}(u)$ as the shared pairwise key between nodes u and v , and distributes the key-plus-id combination $(SK_{u,v}, v)$ to u . After deployment of sensor node u , it establishes direct pairwise keys using direct key establishment phase of IBPRF with the physical neighbors for which the ids are in u 's key ring K_u .

Now, if u finds still poor connectivity after direct key establishment, it can perform path key establishment stage with 2 or 3 hops.

3 Analysis

In this section, we shall now compute the probability of establishing direct keys between two sensor nodes during direct key establishment, and the probability of establishing a pairwise key between two sensor nodes during path key establishment. We shall also analyze the storage overhead and the communication overhead required by our scheme.

3.1 Probability of Establishing Direct Keys

Let p be the probability that two physical neighbors can establish a direct pairwise key. For the derivation of p , we first observe that two physical neighbors u and v can establish a pairwise key only if the key ring K_u of node u contains the shared secret key $SK_{u,v} = PRF_{MK_v}(u)$ and the id of node v , or the key ring K_v of node v contains the shared secret key $SK_{v,u} = PRF_{MK_u}(v)$ and the id of node u because of the fact that any of nodes u and v can

initiate for establishing a pairwise key between them.

We then have, $p = 1 -$ (probability that both u and v do not establish a pairwise key). The total number of ways to select m ids from the pool N of size n is $\binom{n}{m}$. For a fixed key ring K_u of node u , the total number of ways to select K_v of a node v such that K_v does not have the id of u is $\binom{n-1}{m}$. Thus, we have

$$p = 1 - \frac{\binom{n-1}{m}}{\binom{n}{m}} = \frac{m}{n}. \quad (1)$$

We note that p strictly depends on the network size n and the key ring size.

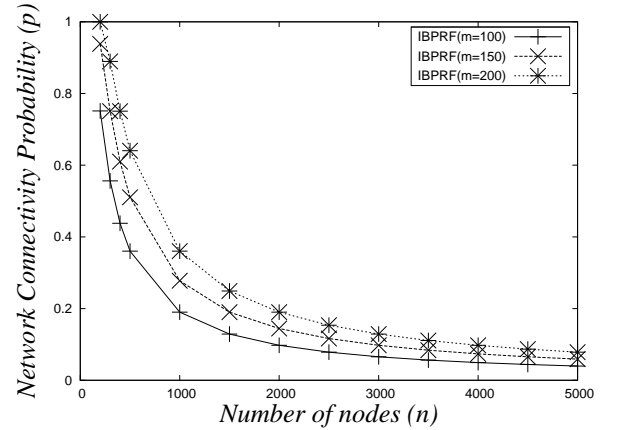


Figure 1: The probability p that two sensors establish a direct pairwise key v.s. the network size n , with $m = 100, 150, 200$.

It is clear from Figure 1 that when the network size is small, our scheme provides better connectivity. Therefore, our scheme can not support a large network. In section 5, we have proposed an improved version of our scheme to support large networks.

3.2 Probability of Establishing Keys using 1-hop Path Key Establishment

If d be the average number of neighbor nodes that each sensor node can contact, it follows from the similar analysis in [8] that the probability of two sensor nodes establishing a pairwise key (directly or indirectly) is

$$p_s = 1 - (1 - p)(1 - p^2)^d. \quad (2)$$

The network connectivity probabilities for path key establishment with 1-hop are plotted in Figure 2. From this

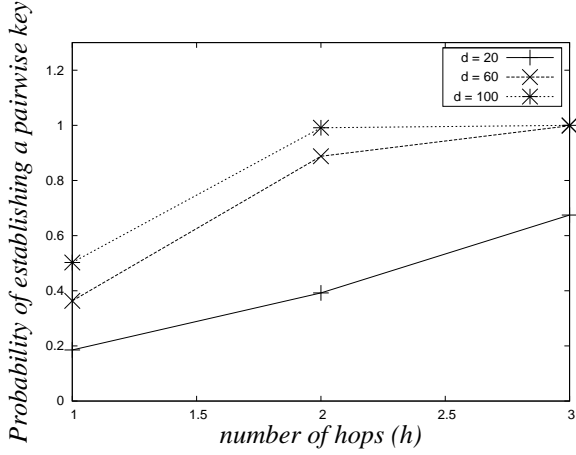


Figure 2: The probability p_s of establishing a pairwise key v.s. the probability p that two sensor nodes establish a direct pairwise key, with $d = 20, 60, 100$.

figure it is also clear that we are able to achieve better connectivity after executing this stage even if the network is almost disconnected initially.

3.3 Calculation of Storage Overhead

Each sensor node has to store a master key which is shared with the key setup server and m predistributed key-plus-id combinations. Hence, our scheme requires a storage overhead of maximum $m + 1$ keys for each sensor node.

3.4 Calculation of Communication Overhead

For establishing a pairwise key between two sensor nodes u and v , one of them, say u , initiates a request message to node v that its key ring contains the shared key between them. Then, after receiving such a request, node v computes the shared key between u and v by performing only one efficient PRF operation. Hence, the communication overhead involves only one short message for informing the other node that it has a pairwise key and the computational overhead due to single efficient PRF operation.

4 Security Considerations

The security of IBPRF depends on the following facts:

- The security of PRF [7].
- A node's master key MK which is shared with the key setup server.

It is observed that if a node's master key is not disclosed, no matter how many pairwise keys generated by this master key are disclosed, the task is still computationally difficult

for an adversary to recover the master key MK as well as the non-disclosed pairwise keys generated with different ids of sensor nodes. Again, each pre-distributed pairwise key between two sensor nodes is generated by using PRF function randomly. Thus, no matter how many sensor nodes are compromised, the direct pairwise keys between non-compromised nodes are still secure. In other word, node compromise does not eventually lead to compromise of the direct pairwise keys between the other non-compromised nodes. In this way, our scheme provides perfect security against node captures.

5 The Improved Scheme

We note that our basic scheme (IBPRF) provides better connectivity if the network size is small, whereas it provides perfect security against node captures. In fact, there is no communication overhead during establishment of the direct pairwise keys between sensors and also during the addition of nodes after their initial deployment.

To support a large sensor network, we wish to apply our basic scheme in distributed sensor networks. The deployment region is divided into c number of sub-regions called the cells such that each cell can communicate with the base stations comfortably. Let the i -th cell be denoted by $cell_i$. Assume that each $cell_i$ contains n_i number of sensor nodes. In practical situation, it is not always possible to deploy each node to a pre-determined location in the deployment region. We further assume that the key setup server only knows the nodes containing to a particular cell which will be deployed in that region randomly. In practice, this assumption is appropriate. Under this configuration, we now apply our basic scheme to each cell as follows.

Let N_i be the pool of the ids of n_i sensor nodes in a cell $cell_i$. Assume that each sensor node u is capable of holding a total of $m + 1$ cryptographic keys. In key pre-distribution phase, for each node $u \in cell_i$, the key setup server randomly generates a master key MK_u . For each node $u \in cell_i$, the key setup server also selects a set S of m randomly generated ids of the sensor nodes from the pool N_i . For each $v \in S$, the key setup server generates a symmetric key $SK_{u,v} = PRF_{MK_v}(u)$ as the pairwise key shared between nodes u and v , where MK_v is the master key for node v and u is the id for node u . The key-plus-id combination $(SK_{u,v}, v)$ is stored in u 's key ring K_u . After deployment of the sensor nodes, they establish direct pairwise keys using direct key establishment phase of our basic scheme (IBPRF). The other phases like path key establishment, mobility of sensor nodes, and addition of sensor nodes remain same as our basic scheme.

Thus, sensor nodes in each cell establish pairwise keys between them and communicate with each other in that cell securely. For mobility of the sensor nodes, we restrict the sensor nodes to move in a particular cell only.

Let p_i denote the probability that two sensor nodes in the i -th cell $cell_i$ can establish a direct pairwise key between them. Similar to analysis in 3.1, we have

$$p_i = 1 - \frac{\binom{n_i - 1}{m}}{\binom{n_i}{m}} = \frac{m}{n_i}. \quad (3)$$

The (average) probability that two sensor nodes in a network of size $n = \sum_{i=1}^c n_i$, establish a direct pairwise key between them is given by

$$p = \frac{\sum_{i=1}^c p_i}{c}. \quad (4)$$

Hence, we are able to achieve better connectivity for the entire network by using our improved version and selecting the appropriate size of the cells. However, the communication overhead as well as resilience measurement against node captures remain same as our basic scheme (IBPRF). We note that this improved scheme may not always work for ad hoc mode sensor networks.

6 Comparison with Previous Schemes

In this section, we compare both our basic scheme (IBPRF) and the improved scheme with the EG [6], the q -composite (qC) [3], and the polynomial-pool based [8] schemes with respect to the communication overhead, network connectivity and resilience against node captures.

(1) Communication overhead

For the EG and the q -composite schemes, when a node wishes to establish pairwise keys with its physical neighbor nodes, it needs to send a list of some messages encrypted by keys in its key ring.

In case of the polynomial-pool based scheme, a sensor node also needs to send a list of some messages encrypted by potential pairwise keys based on its polynomial shares for establishing a direct pairwise key with a physical neighbor.

Thus, the communication overhead is on the order of the key ring size for these schemes. But, for our schemes, the communication overhead is only due to one short message sent by a node to inform its physical neighbor that it has

a pairwise key in its key ring and a single efficient PRF operation for computing the shared key SK by the physical neighbor. Hence, both our basic scheme (IBPRF) and the improved scheme have much less communication overhead than the EG, the q -composite, and the polynomial-pool based schemes.

(2) Resilience against node capture

From the analysis of the EG scheme [6] and the q -composite scheme [3], it follows that even if the number of nodes captured is small, these schemes may reveal a large fraction of pairwise keys shared between non-compromised sensors. The analysis of the polynomial-pool based scheme [8] shows that this scheme is unconditionally secure and t -collusion resistant. Thus, it has better resilience against node captures than the EG and the q -composite schemes. However, both our basic scheme (IBPRF) and the improved scheme provide perfect security against node captures.

(3) Network connectivity

For the EG scheme [6], the probability of establishing a direct pairwise key between two sensor nodes is

$$p_{EG} = 1 - \frac{\binom{M-m}{m}}{\binom{M}{m}} = 1 - \prod_{i=0}^{m-1} \frac{M-m-i}{M-i} \quad (5)$$

where M and m are the key pool size and key ring size of a sensor node.

For the q -composite scheme [3], the probability of establishing a direct pairwise key between two sensor nodes is

$$p_{qC} = 1 - \sum_{i=0}^{q-1} p_i \quad (6)$$

$$\text{where } p_i = \frac{\binom{M}{i} \binom{M-i}{2(m-i)} \binom{2(m-i)}{m-i}}{\binom{M}{m}^2}, \quad M \text{ is}$$

the key pool size and m is the key ring size of a sensor node.

For the polynomial-pool based scheme [8], the probability of establishing a direct pairwise key between two sensor nodes is

$$p_{poly-pool} = 1 - \frac{\binom{s-s'}{s'}}{\binom{s}{s'}} = 1 - \prod_{i=0}^{s'-1} \frac{s-s'-i}{s-i} \quad (7)$$

where s is the polynomial-pool size and s' is the number of shares given to a sensor node. Thus, we see that the EG

and the q -composite schemes depend on M and m . The polynomial-pool based scheme depends on s and s' and the maximum supported network size is bounded by $\frac{(t+1)s}{s'}$, where t is the degree of the symmetric bivariate polynomial, whereas our scheme depends on the network size n and the key ring size m .

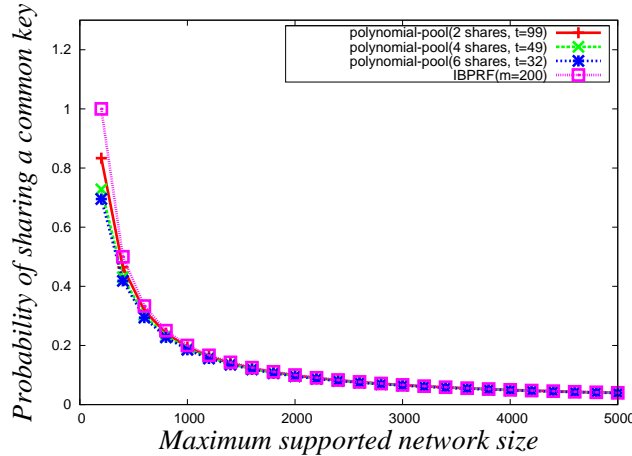


Figure 3: The probability p of establishing a common key v.s. the maximum supported network size n in order to be resilient against node compromise. Assume that each sensor node is capable of holding 200 keys.

For comparison of network connectivity, we only consider the polynomial-pool based scheme because it is more resilient against node compromise than the EG scheme and the q -composite scheme. However, both the EG scheme and the q -composite scheme support networks of arbitrarily big sizes. The relationship between the probability of establishing direct keys and the maximum supported network size for the polynomial-pool based scheme and our basic scheme (IBPRF) is shown in Figure 3. We assume that each sensor is capable of storing 200 keys in its key ring. From this figure, it is very clear that our scheme provides better connectivity than the polynomial-pool based scheme in order to be resilient against node compromise.

7 Conclusion

Our basic scheme (IBPRF) is an alternative to direct key establishment of the bootstrapping protocol. Both IBPRF and the improved scheme guarantee that they have better trade-off between communication overhead, network connectivity and also resilience against node captures compared to the EG, the q -composite, and the polynomial-pool based schemes. Both schemes can also be adapted for mobile sensor networks by initiating direct key establishment phase and one can achieve reasonable connectivity by applying these schemes.

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